Studying the relationship between shipping accident occurrences and variations in cargo ship density over multiple years in the Baltic Sea

Yourfee Kennedy, Biosphere Reserves Management, MSc. Eberswalde University for Sustainable Development, Germany.

Abstract

This research delves into examining the correlation between occurrences of shipping accidents and fluctuations in the density of cargo ships within the Baltic Sea region. By utilizing data spanning from 1989 to 2022 on both shipping accidents and cargo ship density, an analysis is conducted on the temporal and spatial distribution of these accidents and patterns of ship traffic. The outcomes of the study disclose discernible trends in the taking place of accidents, as certain years display an escalated risk linked to heightened ship density. The spatial examination accentuates regions with intense ship traffic aligning with frequent accident-prone areas. The discoveries underscore the significance of comprehending the intricate interaction between maritime traffic patterns and safety results to guide proficient management approaches for bolstering maritime safety in the Baltic Sea. Further exploration in this domain could delve into additional variables like meteorological conditions and vessel attributes to refine the precision of the analysis and foster sustainable practices in maritime transportation.

Keywords: shipping accidents, cargo ship density, maritime safety, Baltic Sea, spatial analysis, temporal distribution, accident hotspots, ship traffic patterns, risk assessment, and marine transportation.

1 Introduction

The Baltic Sea stands as one of the busiest maritime regions globally, serving as a crucial conduit for global alternate and transportation. but, with extended maritime site visitors comes a heightened chance of delivery injuries, which pose huge threats to human safety and environmental sustainability. knowledge of the complicated interaction among shipping twist of fate occurrences and versions in shipment ship density is paramount for growing powerful maritime safety strategies and mitigating ability dangers in this crucial maritime area. Maritime transportation plays an essential position in facilitating worldwide exchange and commerce, with approximately of worldwide exchange quantity being transported by using sea (UNCTAD, 2020, COWI, 2011, Jolma and Haapasaari, 2014, Lehikoinen et al., 2013). As a semi-enclosed sea bordered by way of nine countries in Northern Europe, the Baltic Sea witnesses' full-size maritime traffic, encompassing a various range of vessels transporting items, passengers, and commodities throughout international waters (Montewka et al., 2013). however, the place's strategic importance as a prime maritime thoroughfare is coupled with inherent maritime safety and environmental safety challenges. Delivery injuries within the Baltic Sea vicinity pose multifaceted challenges, which include the hazard of vessel collisions, groundings, oil spills, and environmental pollution (H Montewka et al., 2010b, Van Dorp and Merrick, 2011). The elaborate network of transport lanes, dense maritime visitors, negative weather situations, and navigational risks contribute to the heightened vulnerability of the Baltic Sea to transport injuries (Wang et al., 2018). furthermore, the region's specific environmental traits, which include its sensitive atmosphere and susceptibility to ice cover at some stage in ice months, further exacerbate the complexities of maritime protection management (Aven and Guikema, 2011, Rosqvist, 2010,) regardless of efforts to enhance maritime protection and accident prevention measures, the Baltic Sea keeps reveling in a great frequency of shipping injuries, necessitating deeper information of the underlying factors using

a twist of fate occurrences. previous studies have highlighted the importance of spatial evaluation in identifying coincidence hotspots, assessing threat elements, and informing focused interventions for enhancing maritime safety (Christie et al., 2017; Wang et al., 2018). but there remains an essential gap in research focusing especially on the connection between shipping twist of fate occurrences and variations in shipment delivery density over more than one year within the Baltic Sea. In response to this gap, this study seeks to research the relationship between shipping twist of fate occurrences and load ship density variations over multiple years inside the Baltic Sea area. with the aid of leveraging the Geographic records structures (GIS) era, we aim to behaviour a comprehensive spatial and temporal evaluation to resolve the complex dynamics of maritime transportation and coincidence occurrences in this crucial maritime region. via a systematic exam of spatial styles, temporal trends, and statistical correlations, this study endeavors to provide precious insights for maritime protection evaluation and chance control strategies inside the Baltic Sea.

This prolonged introduction gives a comprehensive evaluation of the importance of maritime transportation inside the Baltic Sea place, the demanding situations posed using shipping injuries, and the research hole addressed by using the examination. by way of situating the studies inside the broader context of maritime protection and environmental safety, the advent sets the degree for the subsequent exploration of the relationship between delivery twist of fate occurrences and cargo ship density versions in the Baltic Sea.

2 Literature Review

previous research has highlighted the importance of studying the spatial and temporal dynamics of delivery accidents and their relationship with maritime traffic density. Christie et al. (2017) emphasized the need for complete spatial analysis to identify coincidence hotspots and regions of heightened danger in maritime environments. In addition, Turner et al. (2019) carried out a look at the North Sea location, demonstrating a positive correlation between transport pastime tiers and coincidence occurrences. several research has investigated the factors influencing maritime safety and accident occurrences within the Baltic Sea context. Wang et al. (2018) carried out a spatial analysis of transport accidents in the Baltic Sea, highlighting the role of navigational factors and vessel characteristics in coincidence chance assessment. additionally, (Zhang et al. 2020) explored the impacts of environmental elements which include sea ice dynamics on maritime safety inside the Arctic area, which stocks similarities with the Baltic Sea in phrases of harsh environmental situations. despite the present literature on maritime safety and accident evaluation, there's a superb hole in research specifically that specializes in the relationship between delivery twist of fate occurrences and cargo delivery density over multiple years inside the Baltic Sea. This takes a look at seeking to cope with this gap by utilizing GIS generation to conduct a comprehensive analysis of spatial and temporal styles, aiming to provide precious insights for enhancing maritime protection measures inside the area.

3 Methodology

Records for this study consist of number one datasets: shipping accident occurrences and cargo delivery density over the Baltic Sea. delivery coincidence statistics are acquired from (Meehl et al., 2009; and Trewin and Vermont, 2010) , providing data on accident occurrences which includes date, time, location, and different relevant attributes. shipment delivery density data are derived from raster documents representing ship density over the Baltic Sea for more than one year (e.g., 2019, 2020, 2021, and 2022).

3.1 Data Preprocessing

Earlier than accomplishing spatial evaluation, each dataset undergoes preprocessing steps to ensure information compatibility and accuracy. shipping coincidence records are wiped clean and standardized to dispose of any inconsistencies or mistakes. cargo ship density raster files are processed to extract applicable time-series records for the desired years of analysis (Trigo, 2006; Raible et al., 2008).

3.2 Spatial Analysis

GIS techniques are hired to analyze the relationship between delivery accident occurrences and cargo ship density versions. Spatial overlays are performed to combine accident statistics with shipment deliver density raster layers, making an allowance for the identity of coincidence hotspots and regions of excessive ship density. Statistical analysis is performed to evaluate the correlation between accident occurrences and versions in delivery density over more than one year (Meier et al. (2014).

4 Results

4.1 Temporal Distribution of Shipping Accidents in the Baltic Sea

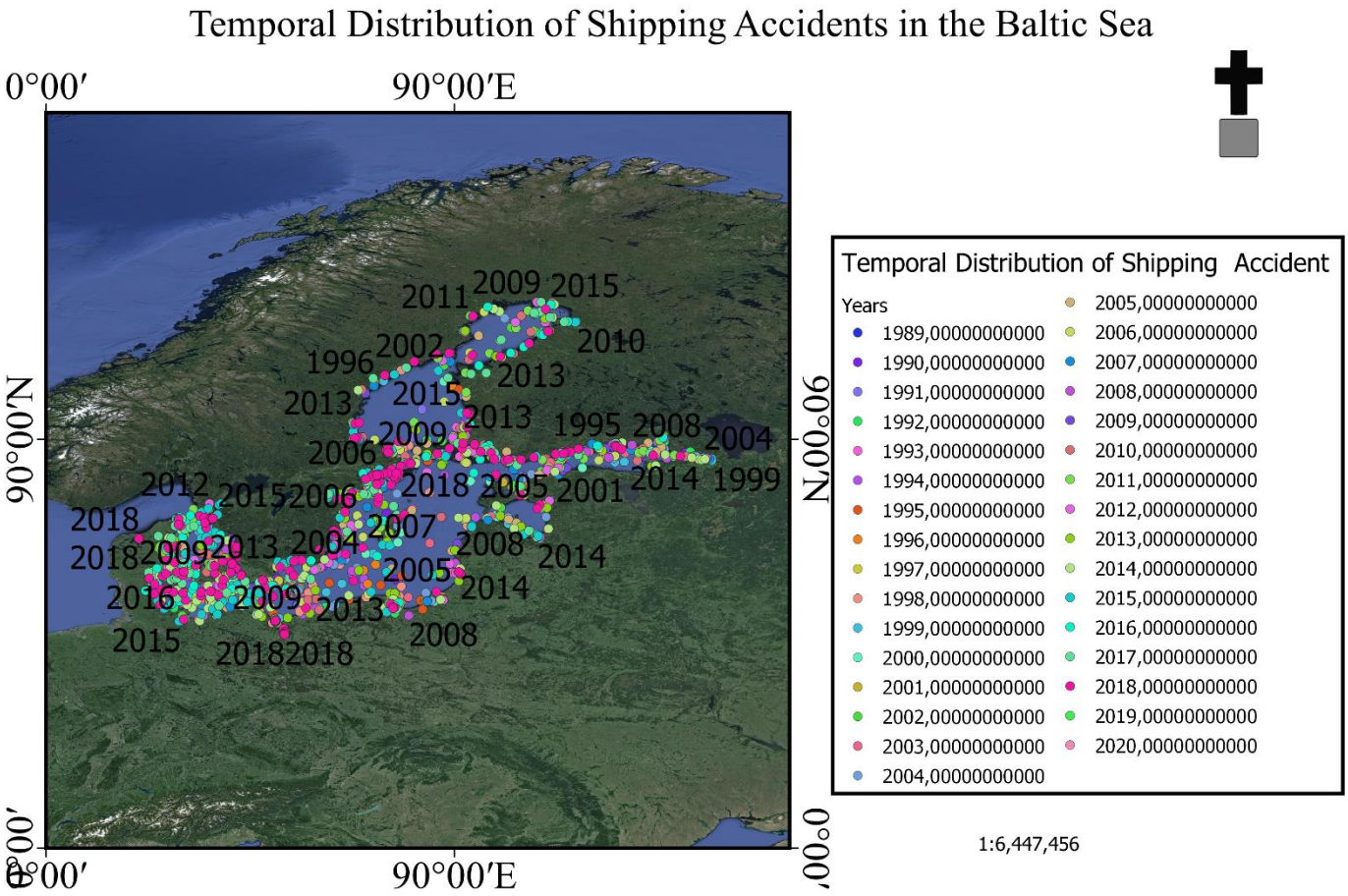

Figure1. .1 Temporal Distribution of Shipping Accidents in the Baltic Sea

4.2 Spatial Distribution of Shipping Accident Types in the Baltic Sea

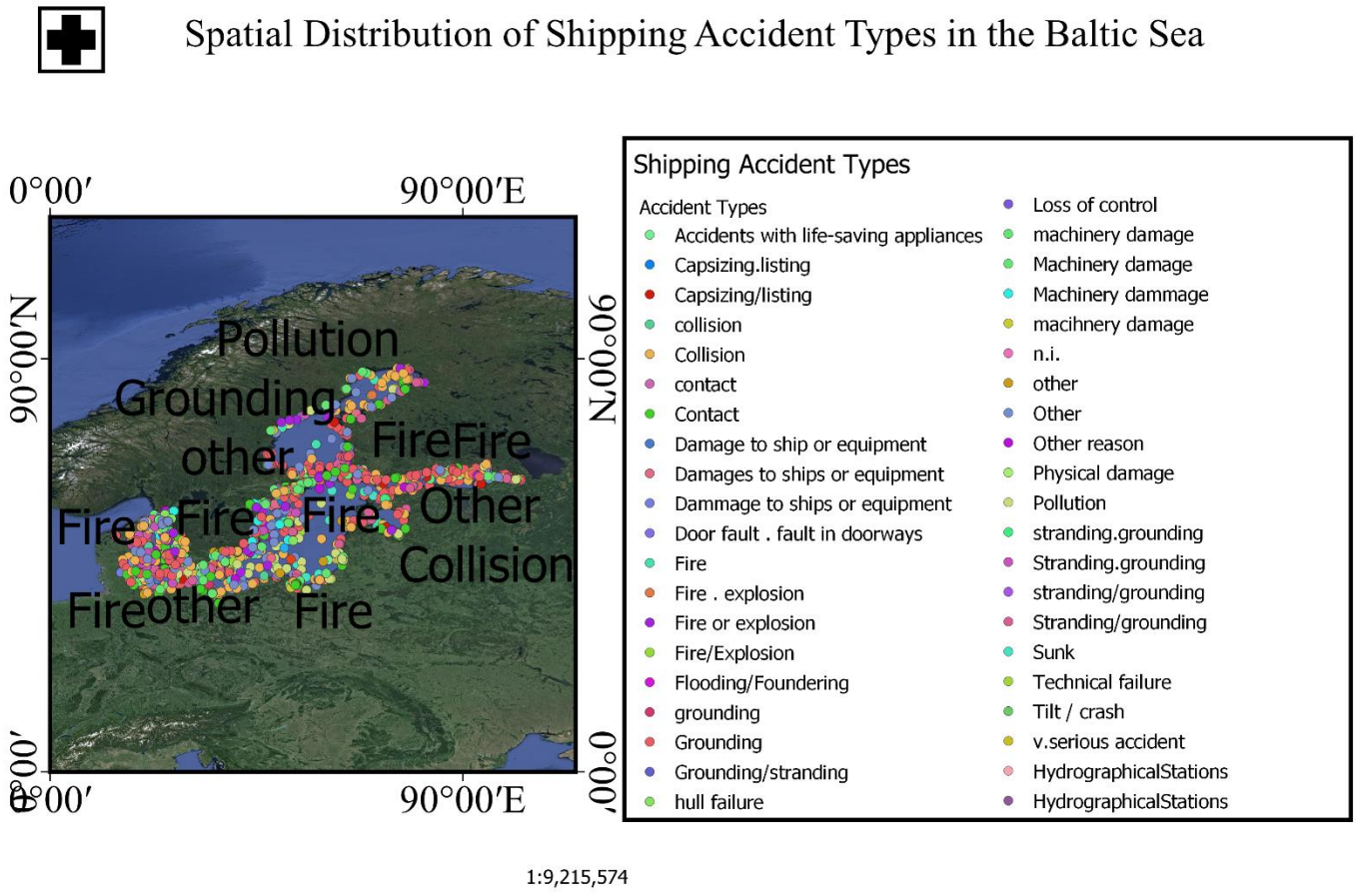

Figure 2. Spatial Distribution of Shipping Accident Types in the Baltic Sea

4.3 Extent of Damage from Shipping Accidents in the Baltic Sea

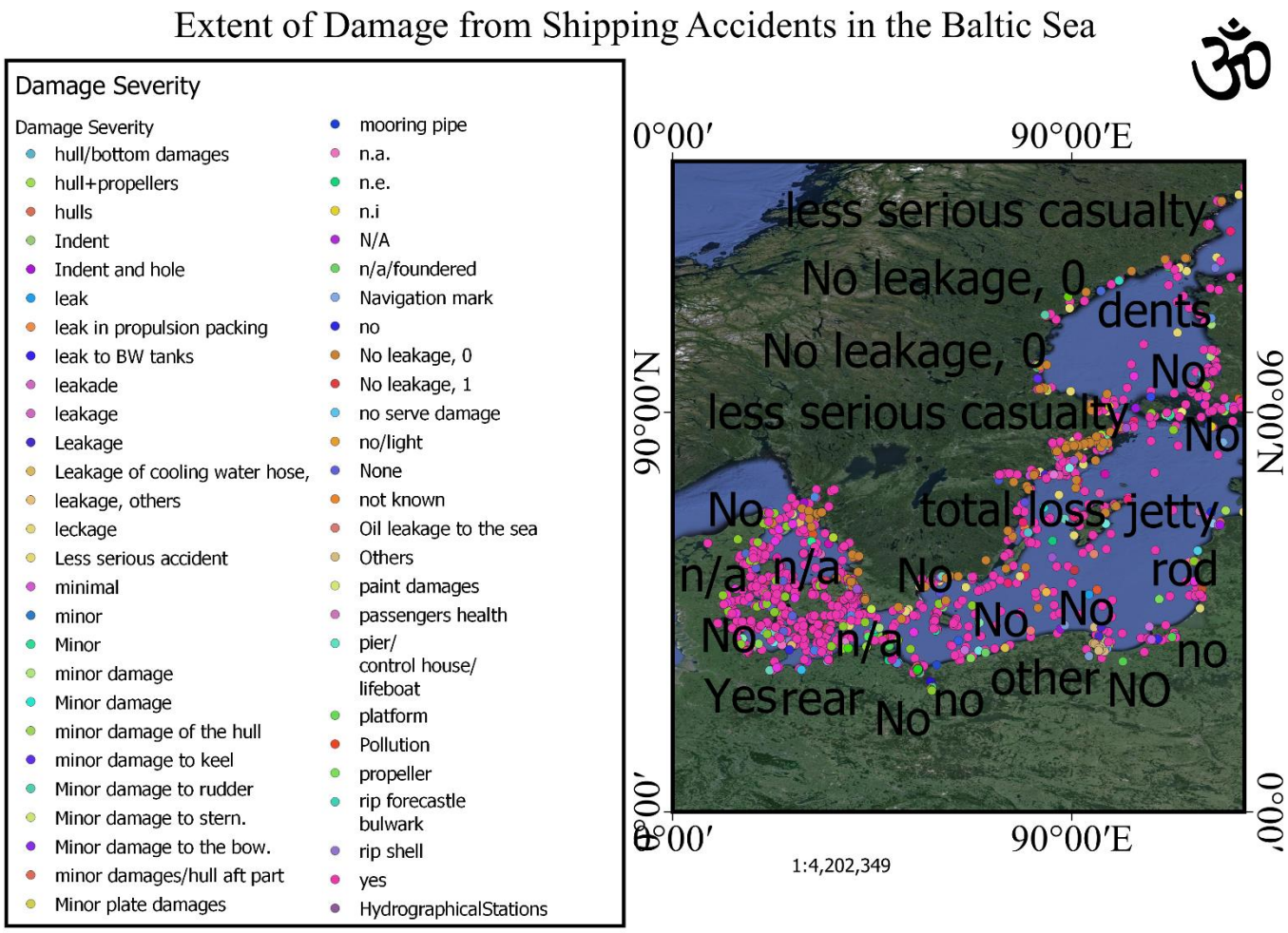

Figure 3. The extent of Damage from Shipping Accidents in the Baltic Sea

4.4 Occurrences of Pollution from Shipping Accidents in the Baltic Sea

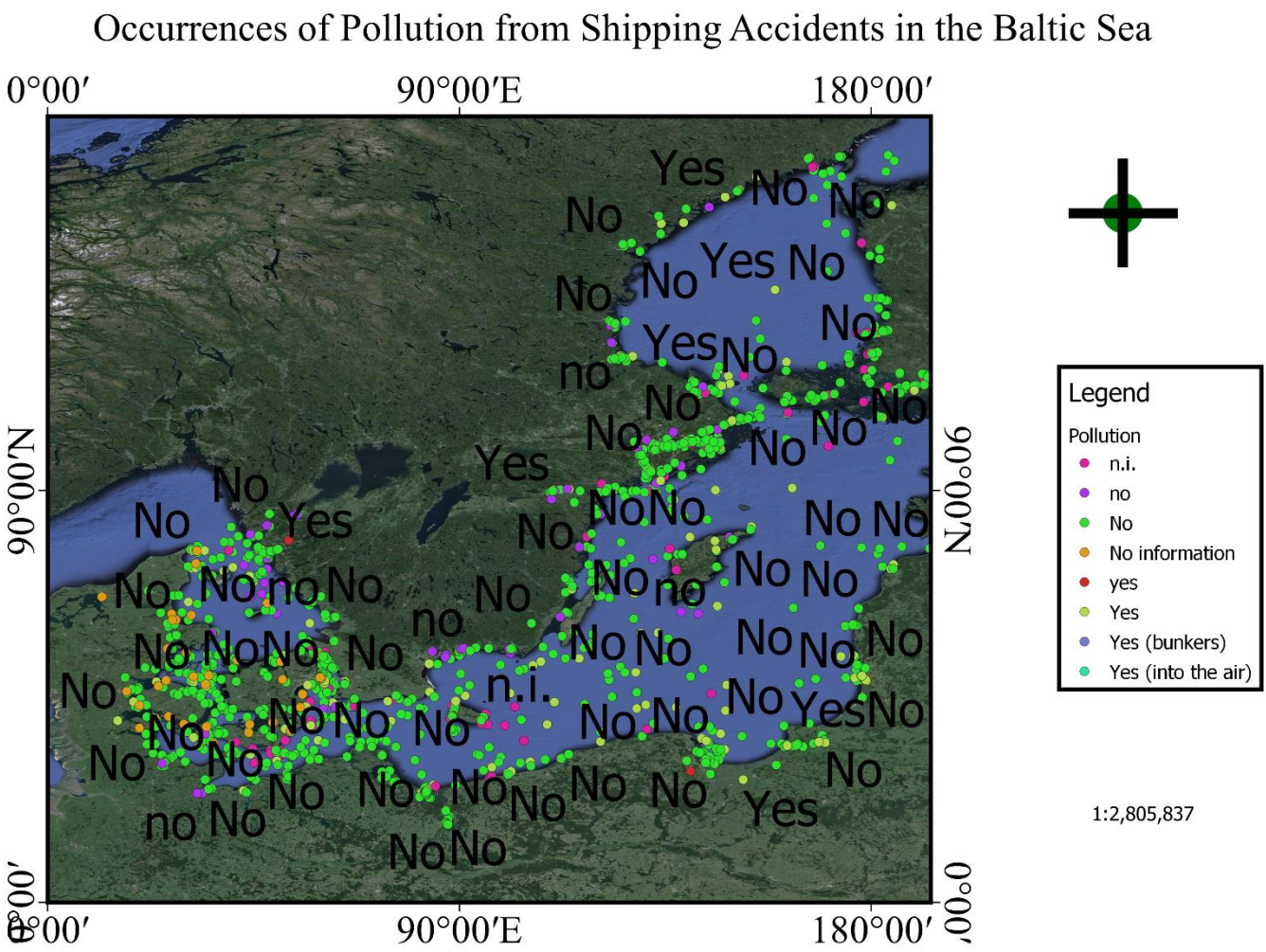

Figure 4. Occurrences of Pollution from Shipping Accidents in the Baltic Sea

4.5 2019 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

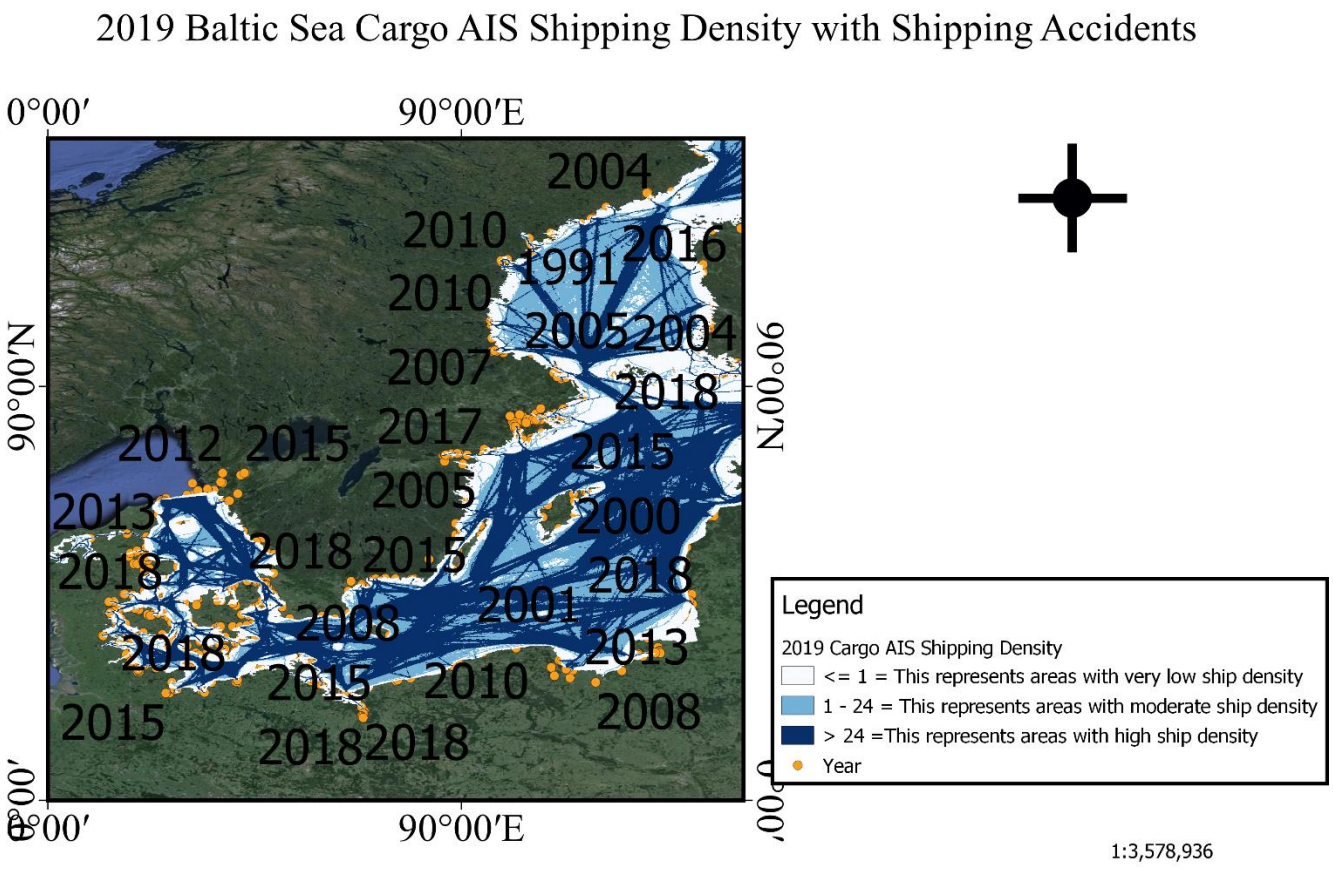

Figure 5.2019 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

4.6 2020 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

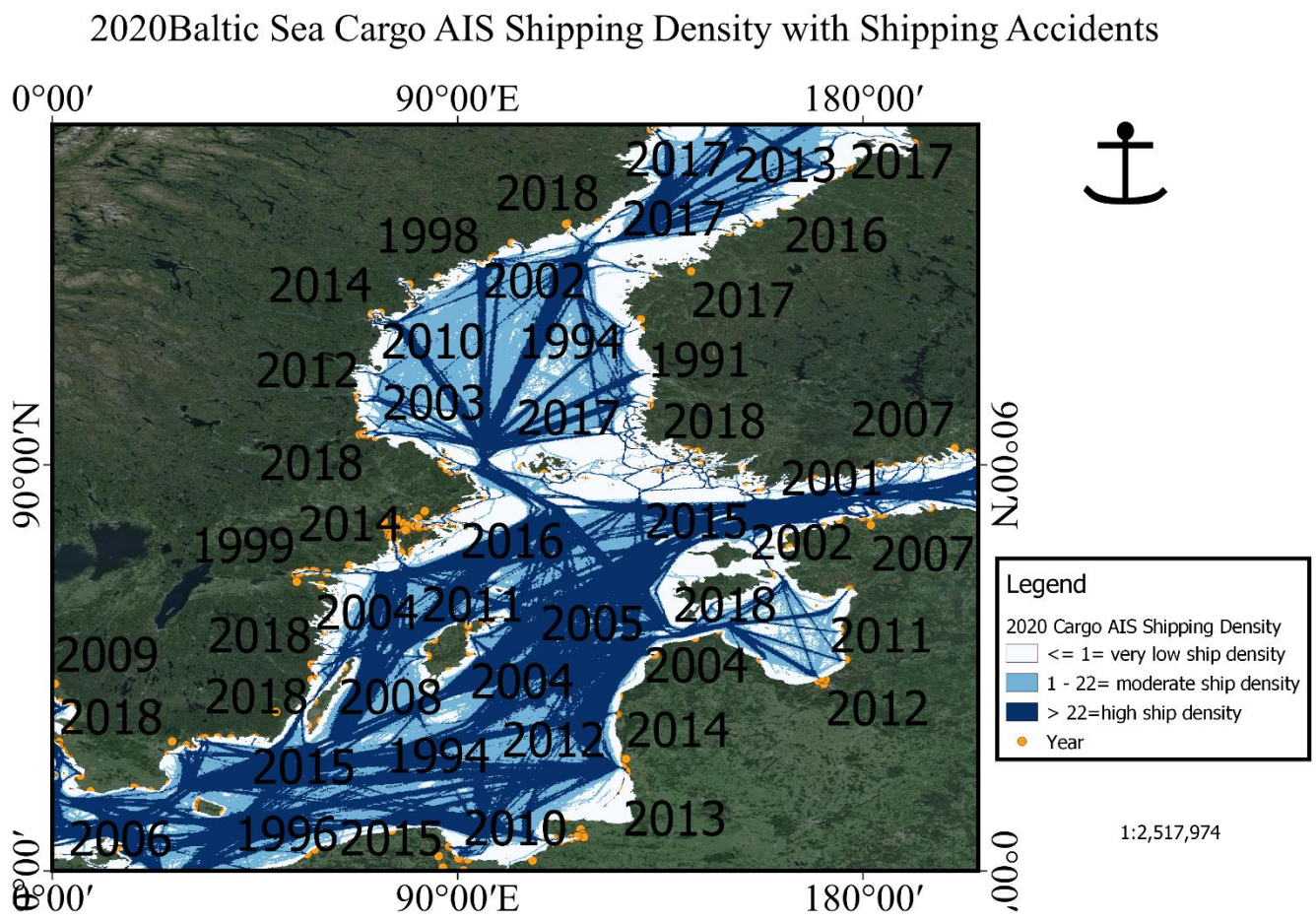

Figure 6. 2020 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

4.7 2021Baltic Sea Cargo AIS shipping Density with Shipping Accident years

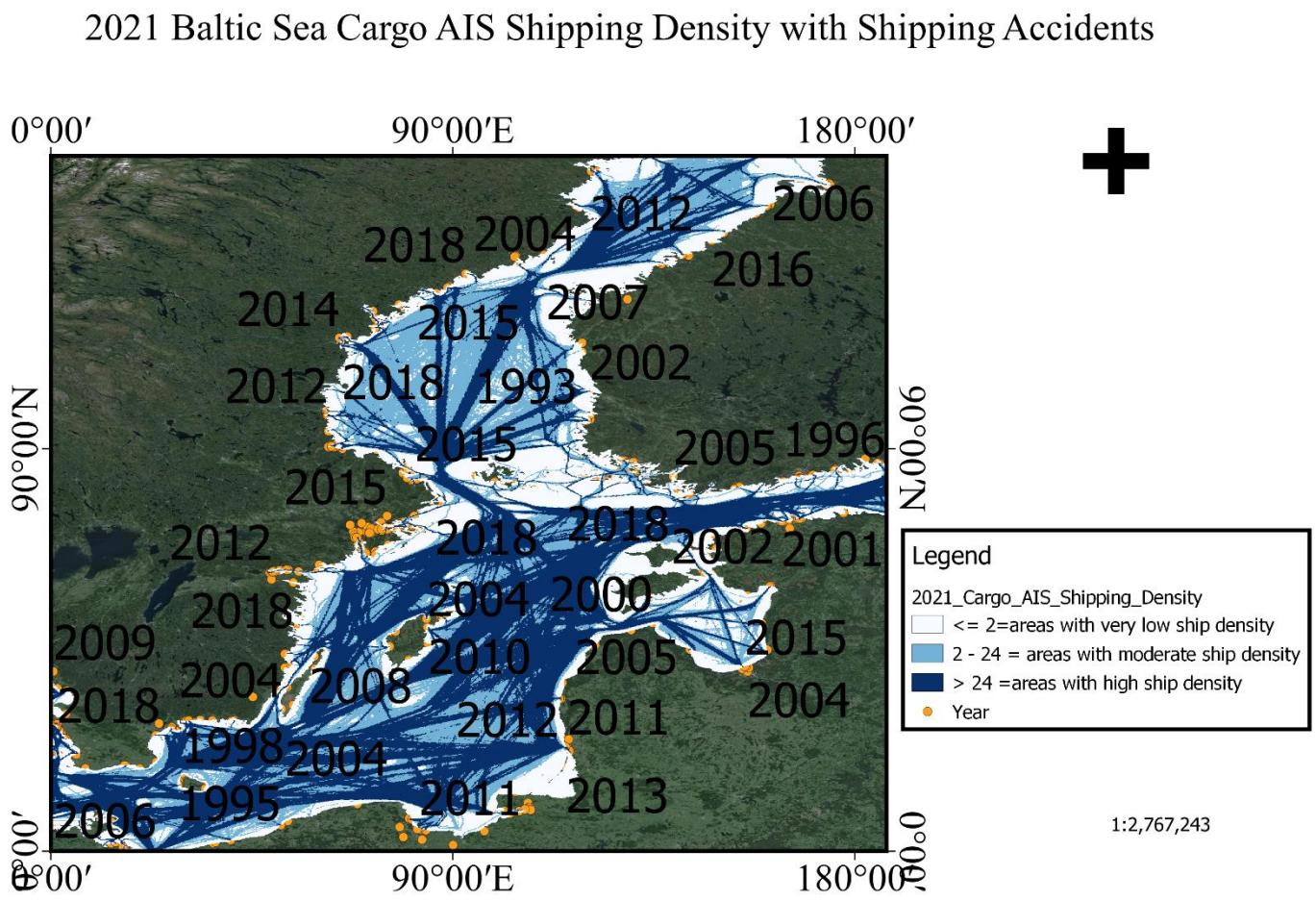

Figure 7.2021 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

4.8 2022 Baltic Sea Cargo AIS shipping Density with Shipping Accident years

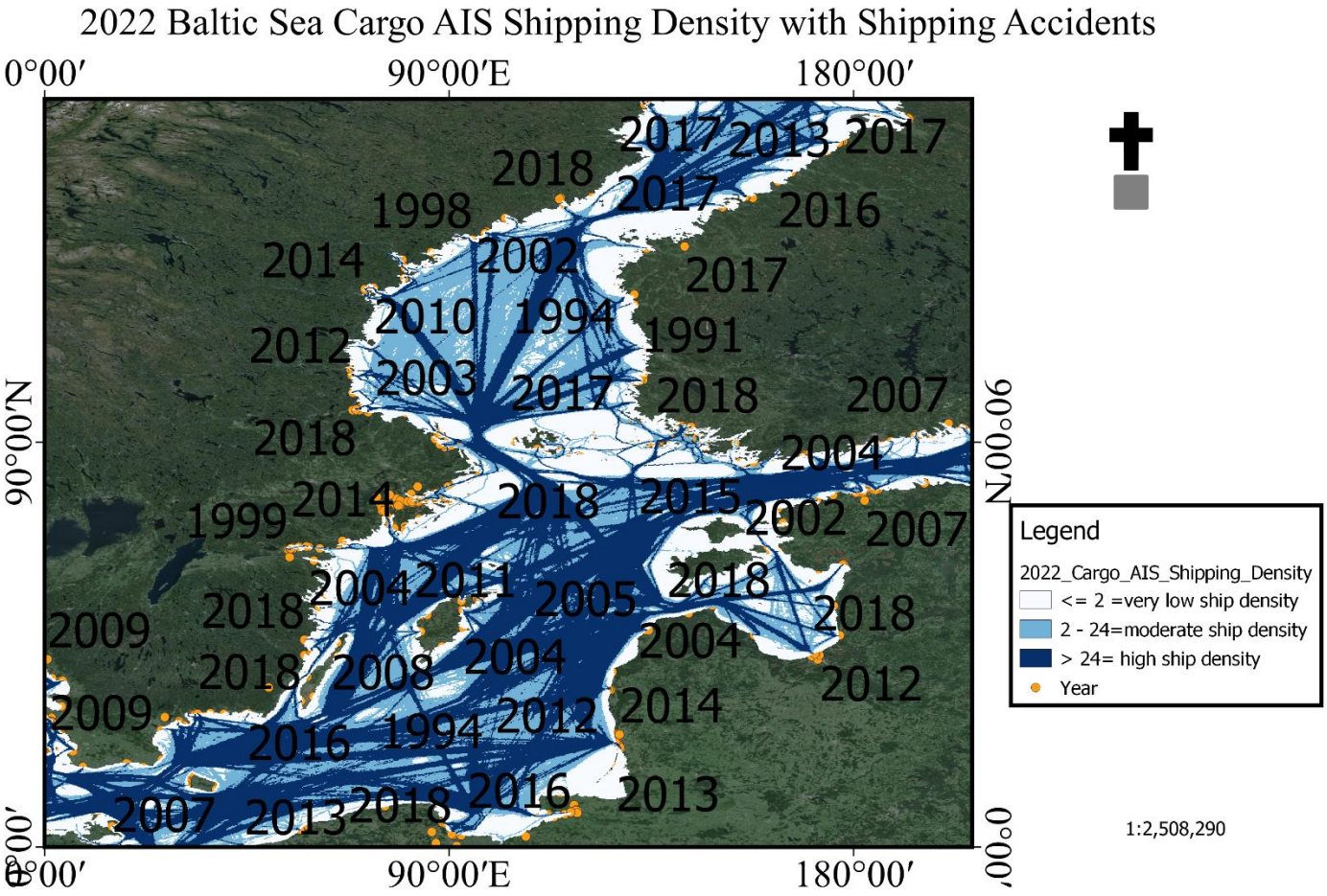

Figure 8.2022 Baltic Sea Cargo AIS Shipping Density with Shipping Accident

5 Discussion

The examination of maritime incidents in the Baltic Sea throughout recent decades unveils several noteworthy discoveries. A visual representation (Figure 1) demonstrates the chronological spread of such incidents from 1989 to 2020 as documented by Pellikka and others (Pellikka et al., 2020). This extensive timeline offers valuable insights into the frequency and occurrence of incidents over time, enabling a more profound comprehension of enduring patterns in nautical safety. Furthermore, Figure 2 illustrates the geographical dispersion of different types of maritime incidents in the Baltic Sea as presented by (Patey and Riska, 1999; Kamesaki et al., 1999; Montewka et al., 2015; Kuuliala et al., 2017 and Bergström et al., 2017). The cartographic depiction outlines diverse incident categories, such as collisions, groundings, spills, and others. Grasping the geographical distribution of incident types is essential for pinpointing areas of high occurrence and trends in incidents, thus guiding targeted measures to bolster maritime safety protocols. Figure 3 highlights the extent of damage resulting from shipping accidents in the Baltic Sea (Lehman et al., 2021; Meier et al., 2021). The map categorizes damage severity into various levels, ranging from less serious to minor damage, pollution, and others. Assessing the extent of damage is essential for evaluating the environmental and economic impacts of accidents and guiding response efforts effectively. Furthermore, Figure 4 showcases the occurrences of pollution resulting from shipping accidents in the Baltic Sea (Willison et al., 2015). The map illustrates that while pollution incidents vary in frequency, the majority of instances indicate no pollution. Understanding the prevalence and distribution of pollution incidents is crucial for mitigating environmental risks and implementing pollution prevention measures. Furthermore, Figure 5 illustrates the 2019 Baltic Sea cargo, AIS, and shipping densities overlayers with shipping accident years (Gröger et al., 2021). The map is classified into 3 categories of ship density which are high, moderate, and very low. The figure

explains the relationship between ship and year, where in some years there is a distinct pattern for ship density and its occurrence for accident. Figure 6 below illustrates the growth of shipping, extending the analysis to 2020. As shipping grew, the potential accident events also increased. Overview, when the ship was dense, the occurrence of the accident was high. It can be seen that the higher the ship density is, the more frequent the accidents are. Furthermore, it has been illustrated by Figure 7 and Figure 8 depict cargo AIS shipping density in the Baltic Sea in 2021 and 2022, respectively (Oikkonen et al., 2016). It has been shown in the maps that there is at least a slight connection between where and when ships are denser around the Baltic Sea and where and when they report accidents mainly in 2021 and 2022.

6 Conclusion

In conclusion, the examination of incidents involving shipping mishaps and fluctuations in the density of cargo vessels in the Baltic Sea underscores the intricate relationship between patterns of maritime traffic and safety consequences. Through the scrutiny of both temporal and spatial patterns in mishaps and vessel density, this investigation offers valuable insights into the improvement of safety protocols at sea and the mitigation of accident risks within the region. The implementation of proficient management approaches guided by these conclusions has the potential to uphold marine ecosystems, safeguard coastal populations, and promote sustainable practices in maritime transportation within the Baltic Sea. Subsequent research endeavors in this domain may consider the integration of supplementary data sources, such as meteorological conditions and vessel attributes, to elevate the precision and resilience of the analysis. Furthermore, the continuous monitoring and assessment of safety protocols at sea are imperative to ensure the sustained efficacy of interventions aimed at curbing shipping mishaps in the Baltic Sea (Cahill, 2002, Wang et al., 2013, (Smailys and Česnauskis, 2006, Hogström,

2012, Klanac et al., 2010, Kujala, 2017, Seneviratne et al., 2012, Meehl et al., 2009; Trewin and Vermont, 2010)).

7 References

Hakanen, P., Suikkanen, S., Franzén, J., Franzén, H., Kankaanpää, H., and Kremp, A.: Bloom and toxin dynamics of *Alexandrium ostenfeldii* in a shallow embayment at the SW coast of Finland, northern Baltic Sea, Harmful Algae, 15, 91–99, 2012.

Hansom, J. D., Switzer, A. D., and Pile, J.: Extreme Waves: Causes, Characteristics, and Impact on Coastal Environments and Society, chap. 11, edited by: Shroder, J. F., Ellis, J. T., and Sherman, D. J., in: Hazards and Disasters Series, Coastal and Marine Hazards, Risks, and Disasters, Elsevier, 307–334, ISBN 9780123964830, https://doi.org/10.1016/B978-0-12-396483-0.00011-X, 2015.

Heinonen, J., Rissanen, S., Kurkela, J., Tikanmäki, M., and Jussila, V.: Ice load portal for preliminary design of offshore wind turbines in the Gulf of Bothnia: case studies, WindEurope Offshore 2019, 26–28 November 2019, Copenhagen, 2019.

HELCOM: HELCOM Baltic Sea Action Plan, available at: http://www.helcom.fi/Documents/Baltic sea action plan/BSAP_Final.pdf (last access: 18 December 2021), 2007.

HELCOM: State of the Baltic Sea: Second HELCOM holistic assessment 2011–2016, in: Baltic Sea Environment Proceedings, 155, 2018.

Hjelmfelt, M. R.: Numerical study of the influence of environmental conditions on lake-effect snowstorms over Lake Michigan, Mon. Weather Rev., 118, 138–150, 1990.

.

Humborg, C., Geibel, M. C., Sun, X., McCrackin, M., Mörth, C.-M., Stranne, C., Jakobsson, M., Gustafsson, B., Sokolov, A., Norkko, A., and Norkko, J.: High emissions of carbon dioxide and methane from the coastal Baltic Sea at the end of a summer heat wave, Frontiers in Marine Science, 6, 493, https://doi.org/10.3389/fmars.2019.00493, 2019.

Hurrell, J.: Hurrell North Atlantic Oscillation (NAO) Index (station-based), available at: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based, last access: 7 December 2021.

Hurrell, J. W.: Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation, Science, 269, 676–679, 1995.

Hurrell, J. W., Kushnir, Y., Ottersen, G., and Visbeck, M.: An overview of the North Atlantic Oscillation, in: The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geoph. Monog. Series, 134, 1–36, 2003.

Hynčica, M. and Huth, R.: Long-term changes in precipitation phase in Europe in cold half year, Atmos. Res., 227, 79–88, 2019.

Ineson, S., Scaife, A. A., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J., Haigh, J. D.: Solar forcing of winter climate variability in the northern hemisphere, Nature Geosci., 4, 753–757, 2011.

Irannezhad, M., Moradkhani, H., and Kløve, B.: Corrigendum to "Spatio-temporal Variability and Trends in Extreme Temperature Events in Finland over the Recent Decades: Influence of Northern Hemisphere Teleconnection Patterns", Adv. Meteorol., 2019, 4857504, https://doi.org/10.1155/2019/4857504, 2019.

Jaagus, J., Briede, A., Rimkus, E., and Remm, K.: Variability and trends in daily minimum and maximum temperatures and in the diurnal temperature range in Lithuania, Latvia and Estonia in 1951–2010, Theor. Appl. Climatol., 118, 57–68, https://doi.org/10.1007/s00704-013-1041-7, 2014.

Jaagus, J., Sepp, M., Tamm, T., Järvet, A., and Mõisja, K.: Trends and regime shifts in climatic conditions and river runoff in Estonia during 1951–2015, Earth Syst. Dynam., 8, 963–976, https://doi.org/10.5194/esd-8-963-2017, 2017.

Jaagus, J., Briede, A., Rimkus, E., and Sepp, M.: Changes in precipitation regime in the Baltic countries in 1966–2015, Theor. Appl. Climatol., 131, 433–443, https://doi.org/10.1007/s00704-016-1990-8, 2018.

Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., and Stipa, T.: A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmos. Chem. Phys., 9, 9209–9223, https://doi.org/10.5194/acp-9-9209-2009, 2009.

Jönsson, A., Broman, B., and Rahm, L.: Variations in the Baltic Sea wave fields, Ocean Eng., 30, 107–126, https://doi.org/10.1016/S0029-8018(01)00103-2, 2003.

Kahru, M., Elmgren, R., and Savchuk, O. P.: Changing seasonality of the Baltic Sea, Biogeosciences, 13, 1009–1018, https://doi.org/10.5194/bg-13-1009-2016, 2016.

Klais, R., Tamminen, T., Kremp, A., Spilling, K., and Olli, K.: Decadal-scale changes of dinoflagellates and diatoms in the anomalous Baltic Sea spring bloom, PLoS ONE, 6, e21567, https://doi.org/10.1371/journal.pone.0021567, 2011.

Kollanus, V., Tiittanen, P., and Lanki, T.: Mortality risk related to heatwaves in Finland – Factors affecting vulnerability, Environ Res., 201, 111503, https://doi.org/10.1016/j.envres.2021.111503, 2021.

Kudryavtseva, N., Räämet, A., and Soomere, T.: Coastal flooding: joint probability of extreme water levels and waves along the Baltic Sea coast, in: Global Coastal Issues of 2020, edited by: Malvárez, G. and Navas, F., J. Coast. Res., Special Issue No. 95, 1146–1151, 2020.

Kujala, P.: Damage Statistics of Ice-strengthened Ships in the Baltic Sea 1984–1987, Espoo, Finland: Winter Navigation Research Board, Research Report No. 47., 62 pp., 1991.

Larjavaara, M., Kuuluvainen, T., and Rita, H.: Spatial distribution of lightning-ignited forest fires in Finland, Forest Ecol. Manag., 208, 177–188, 2005a.

Larjavaara, M., Pennanen, J., and Tuomi, T.: Lightning that ignites forest fires in Finland, Agr. Forest Meteorol., 132, 171–180, 2005b.

Lehtonen, I., Ruosteenoja, K., and Jylhä, K.: Projected changes in European extreme precipitation indices on the basis of global and regional climate model ensembles, Int. J. Climatol., 34, 1208–1222, 2014a.

Lehtonen, I., Ruosteenoja, K., Venäläinen, A., and Gregow, H.: The projected 21st century forest-fire risk in Finland under different greenhouse gas scenarios, Boreal Environ. Res., 19, 127–139, 2014b.

Lehtonen, I., Venäläinen, A., Kämäräinen, M., Peltola, H., and Gregow, H.: Risk of large-scale fires in boreal forests of Finland under changing climate, Nat. Hazards Earth Syst. Sci., 16, 239–253, https://doi.org/10.5194/nhess-16-239-2016, 2016.

Leiding, T., Tinz, B., Rosenhagen, G., Lefevre, C., Haeseler, S., Hagemann, S., Bastigkeit, I., Stein, D., Schwenk, P., Mueller, S., Outzen, O., Herklotz, K., Kinder, F., and Neumann, T.: Meteorological and oceanographic conditions at the FINO platforms during the severe storms Christian and Xaver, DEWI Magazin, 44, 16–25, 2014.

Lenderink, G., Belušić, D., Fowler, H., Kjellström, E., Lind, P., van Meijgaard, E., van Ulft, B., and de Vries, H.: Systematic increases in the thermodynamic response of hourly precipitation extremes in an idealized warming experiment with a convection-permitting climate model, Environ. Res. Lett., 14, 074012, https://doi.org/10.1088/1748-9326/ab214a, 2019.

Lenggenhager, S., Croci-Maspoli, M., Brönnimann, S., and Martius, O.: On the dynamical coupling between atmospheric blocks and heavy precipitation events: a discussion of the southern Alpine flood in October 2000, Q. J. Roy. Meteor. Soc., 145, 530–545, https://doi.org/10.1002/qj.3449, 2019.

Lensu, M., Haapala, J., Lehtiranta, J., Eriksson, P., Kujala, P., Suominen, M., Mård, A., Vedenpää, L., Kõuts, T., and Lilover, M.-J.: Forecasting of compressive ice conditions, in: Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions (POAC'13), available at: https://www.poac.com/Papers/2013/pdf/POAC13_208.pdf (last access: 18 December 2021), 2013.

Leppäranta, M.: The drift of sea ice, 2nd edn., Springer, Heidelberg, https://doi.org/10.1007/978-3-642-04683-4, 2011

Leppäranta, M. and Myrberg, K.: Physical Oceanography of the Baltic Sea, Springer, Berlin, Heidelberg, New York, 378 pp., 2009.

Lind, P. and Kjellström, E.: Water budget in the Baltic Sea drainage basin: Evaluation of simulated fluxes in a regional climate model, Boreal Environ. Res., 14, 56–67. 2009.

Peings, Y. and Magnusdottir, G.: Wintertime atmospheric response to Atlantic multidecadal variability: effect of stratospheric representation and ocean–atmosphere coupling, Clim. Dynam., 47, 1029–1047, https://doi.org/10.1007/s00382-015-2887-4, 2016.

Pellikka, H., Laurila, T. K., Boman, H., Karjalainen, A., Björkqvist, J.-V., and Kahma, K. K.: Meteotsunami occurrence in the Gulf of Finland over the past century, Nat. Hazards Earth Syst. Sci., 20, 2535–2546, https://doi.org/10.5194/nhess-20-2535-2020, 2020.

Peterson, T. C. and Manton, M. J.: Monitoring changes in climate extremes: a tale of international collaboration, B. Am. Meteorol. Soc., 89, 1266–1271, 2008.

Pettersson, H. and Jönsson, A.: Wave climate in the northern Baltic Sea in 2004, HELCOM Baltic Sea Environment Fact Sheets, available at: http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/ (last access: 10 September 2015), 2005.

Pettersson, H., Kalén, O., and Brüning, T.: Wave climate in the Baltic Sea in 2017, HELCOM Baltic Sea Environment Fact Sheets, available at: http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/ (last access: 26 March 2019), 2018.

Piotrowski, A., Szczucinski, W., Sydor, P., Kotrys, B., Rzodkiewicz, M., and Krzyminska, J.: Sedimentary evidence of extreme storm surge or tsunami events in the southern Baltic Sea (Rogowo area, NW Poland), Geol. Q., 61, 973–986, 2017.

Prahl, B. F., Boettle, M., Costa, L., Kropp, J. P., and Rybski, D.: Damage and protection cost curves for coastal floods within the 600 largest European cities, Sci. Data, 5, 180034, https://doi.org/10.1038/sdata.2018.34, 2018.

Pryor, S. C., Barthelmie, R. J., Clausen, N. E., Drews, M., MacKeller, N., and Kjellström, E.: Analysis of possible changes in intense and extreme wind speeds over Northern Europe under climate change scenarios, Clim. Dynam., 38, 189–208, 2012.

Punkka, A.-J.: Mesoscale convective systems in Finland, Finnish Meteorological Institute Contributions, 116, Helsinki, Finland, available at; http://urn.fi/URN:ISBN:978-951-697-866-9 (last access: 8 December 2021), 2015.

Räämet, A. and Sommer, T.: The wave climate and its seasonal variability in the northeastern Baltic Sea, Est. J. Earth Sci., 59, 100–113, https://doi.org/10.3176/earth.2010.1.08, 2010.

Rauthe, M., Steiner, H., Riediger, U., Mazurkiewicz, A., and Gratzki, A.: A Central European precipitation climatology – Part I: Generation and validation of a high-resolution gridded daily data set (HYRAS), Meteorol. Z., 22, 235–256, https://doi.org/10.1127/0941-2948/2013/0436, 2013.

Ravestein, P., van der Schrier, G., Haarsma, R., Scheele, R., and van den Broek, M.: Vulnerability of European intermittent renewable energy supply to climate change and climate variability, Renew. Sust. Energ. Rev., 97, 497–508, https://doi.org/10.1016/j.rser.2018.08.057, 2018.

Reckermann, M., Omstedt, A., Soomere, T., Aigars, J., Akhtar, N., Bełdowska, M., Bełdowski, J., Cronin, T., Czub, M., Eero, M., Hyytiäinen, K. P., Jalkanen, J.-P., Kiessling, A., Kjellström, E., Kuliński, K., Larsén, X. G., McCrackin, M., Meier, H. E. M., Oberbeckmann, S., Parnell, K., Pons-Seres de Brauwer, C., Poska, A., Saarinen, J., Szymczycha, B., Undeman, E., Wörman, A., and Zorita, E.: Human impacts and their interactions in the Baltic Sea region, Earth Syst. Dynam. Discuss. [preprint], https://doi.org/10.5194/esd-2021-54, in review, 2021.

Reihan, A., Koltsova, T., Kriaučiūnienė, J., Lizuma, L., and Meilutytė-Barauskienė, D.: Changes in water discharges of the Baltic states rivers in the 20th century and its relation to climate change, Nord Hydrol., 38, 401–412, 2007.

Rennert, K. J. and Wallace, J. M.: Cross-frequency coupling, skewness, and blocking in the northern hemisphere winter circulation, J. Climate, 22, 5650–5666, 2009.

Reusch, T. B. H., Dierking, J., Andersson, H. C., Bonsdorff, E., Carstensen, J., Casini, M., Czajkowski, M., Hasler, B., Hinsby, K., Hyytiäinen, K., Johannesson, K., Jomaa, S., Jormalainen, V., Kuosa, H., Kurland, S., Laikre, L., MacKenzie, B. R., Margonski, P., Melzner, F., Oesterwind, D., Ojaveer, H., Refsgaard, J., C., Sandström, A., Schwarz, G., Tonderski, K., Winder, M., and Zandersen, M.: The Baltic Sea as a time machine for the future coastal ocean, Science Advances, 4, eaar8195, https://doi.org/10.1126/sciadv.aar8195, 2018.

Rey, J., Rohat, G., Perroud, M., Goyette, S., and Kasparian, J.: Shifting velocity of temperature extremes under climate change, Environ. Res. Lett., 15, 034027, https://doi.org/10.1088/1748-9326/ab6c6f, 2020.

R'Honi, Y., Clarisse, L., Clerbaux, C., Hurtmans, D., Duflot, V., Turquety, S., Ngadi, Y., and Coheur, P.-F.: Exceptional emissions of NH_3 and HCOOH in the 2010 Russian wildfires, Atmos. Chem. Phys., 13, 4171–4181, https://doi.org/10.5194/acp-13-4171-2013, 2013.

Ribeiro, A., Barbosa, S. M., Scotto, M. G., and Donner, R. V.: Changes in extreme sea-levels in the Baltic Sea, Tellus A, 66, 20921, https://doi.org/10.3402/tellusa.v66.20921, 2014.

Rodwell, M. J., Rowell, D. P., Folland, C. K.: Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, Nature, 398, 320–323, 1999.

Ronkainen, I., Lehtiranta, J., Lensu, M., Rinne, E., Haapala, J., and Haas, C.: Interannual sea ice thickness variability in the Bay of Bothnia, The Cryosphere, 12, 3459–3476, https://doi.org/10.5194/tc-12-3459-2018, 2018.

Rosenhagen, G. and Bork, I.: Rekonstruktion der Sturmflutwetterlage vom 13. November 1872, MUSTOK-Workshop 2008, Siegen, 4–5 March 2008, 2008.

Roudier, P., Andersson, J., Donnelly, C., Feyen, L., Greuell, W., and Ludwig, F.: Projections of future floods and hydrological droughts in Europe under a +2 °C global warming, Climatic Change, 135, 341–355, https://doi.org/10.1007/s10584-015-1570-4, 2016.

Rowe, J. S. and Scotter, G. W.: Fire in the boreal forest, Quaternary Res., 3, 444–464, 1973.